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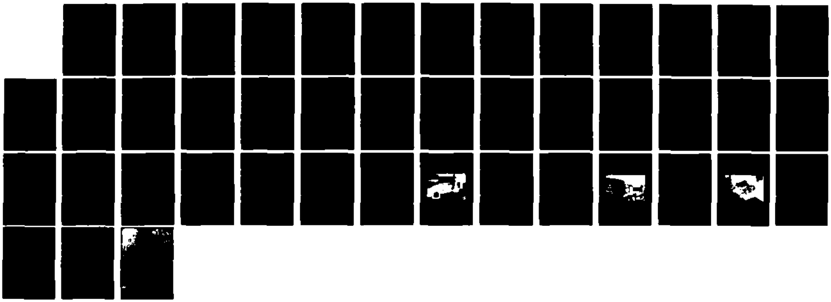

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THE EFFECTS OF ACOUSTIC EXCITATION ON THE MIXING OF TWO PARALLEL LAMINAR STREAMS OF FLUID

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This technical report has been reviewed and is approved for publication.

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TABLE OF CONTENTS

Abstract i
List of figures ii

1. INTRODUCTION 1

2. EXPERIMENTS 3
2.1 Preliminary experiments 3
2.2 Experiments with the L-6 wind tunnel 5

3. LINEAR INSTABILITY THEORY 9

4. EXPERIMENTS BY OTHER RESEARCHERS 11
4.1 Introduction 11
4.2 Boundary layers 11
4.3 Free shear layers 12
4.4 Axisymmetric jets 17
4.5 Mathematical studies 18

5. CONCLUSIONS 20

6. RECOMMENDATIONS 24

REFERENCES 25

FIGURES 27

ABSTRACT

This project consisted of a study of the effects of acoustic excitation on the mixing of two parallel streams. Experiments were performed using two separate facilities and literature pertaining to the subject was reviewed.
It was concluded that acoustic excitation may have a large effect on enhancing the mixing of two parallel streams.
Other conclusions were reached pertaining to the process of the excitation which explain the results of the experiments performed and lead to recommendations for continued work.

LIST OF FIGURES

1	Duct used in preliminary experiments
2a	Wavy pattern in duct
2b	Pattern of vortices in duct
3a	L-6 wind tunnel; side view + front view
3b	L-6 wind tunnel
4a	Wavy pattern from L-6
4b	Pattern of vortices from L-6
5	Siren
6	Experimental arrangement of Browand
7a	Velocity profiles in the duct with the same mean velocity in each side
7b	Velocity profiles in the duct with different mean velocities in the two sides
8a	Velocity profiles for the L-6 with the same mean velocity in each side
8b	Velocity profiles for the L-6 with different mean velocities in the two sides

1. INTRODUCTION

This project consisted of an attempt to enhance the mixing rate of two laminar parallel streams of fluid by means of acoustic excitation. The project follows from one performed last year in which "trip jets" injected normal to the streams were used to increase the mixing rate (Ref. 13). The motive for that project was to improve the efficiency of chemical lasers, whose operation depends on the mixing of a large number of parallel streams of two different fluids.

When this project was started, literature searches were conducted both using a computer and using the VKI card catalogue. No information of much help was found at that time, so it was decided to attempt to study the more fundamental problem of acoustic excitation of flow instabilities. Early experiments performed using facilities from last year's project showed that acoustic excitation could indeed increase the mixing rate of two parallel streams, though the repeatability was low.

Encouraged by these results, it was decided that a new arrangement should be designed which would permit a study of acoustic - flow instability interaction at a fundamental level. The goal of the project would be to gain understanding of the process, and to discover the relevant parameters involved. Since nothing was known at that time about the interaction process, visualization of the experiments seemed the only logical way to proceed, both to provide a quick means to decide if interaction had occurred and possibly to provide some insight into the mechanisms of any interaction seen.

As the experimental apparatus of last year was felt to be unsuitable for a fundamental study, a new experimental arrangement was assembled with several considerations in mind. First, as mentioned earlier, visualization should be possible, as this was felt to be crucial to a qualitative understanding of the process. Secondly, the new arrangement should allow for

as many variable parameters as possible, in order to decide what factors play a role in the process. Finally, the arrangement should permit the use of instruments to make quantitative measurements, if the project were to reach the point where these would add to any qualitative results previously found.

Unfortunately, no enhanced mixing was found using the new experimental facility. In an attempt to understand the reasons why excitation proved possible in the preliminary experiments but not in experiments using the new facility, a study of flow instabilities in general was made. This in turn led to a number of articles on acoustic excitation of flow instabilities which were not found by the previous literature searches. These led to a better understanding of the process and reasons why no excitation was seen using the new facility.

In this project the preliminary experiments will first be described, followed by a description of the new experimental arrangement and the experiments performed using it. A discussion of linear instability theory, which is important in the understanding of the project as a whole, will be given, followed by a discussion of other work done on this topic Finally, there will be a discussion of the project itself, containing comparisons with other work done, conclusions, and recommendations for further work.

2. EXPERIMENTS

2.1 Preliminary experiments

In the preliminary experiments, the duct used in last years' project was used. This is a long duct of dimensions 4.5 cm×20 cm, with a splitter plate .5 cm wide extending part of the length of the duct and dividing it in two vertically (Fig. 1). The duct was long enough that the two streams had parabolic velocity profiles by the time they reached the end of the splitter plate, after which they mixed. Due to the large height-width ratio, the flows were nearly two dimensional. For visualization, air was used in one stream, and air and smoke in the other. The duct donwstream of the splitter plate was constructed of plexiglass.

When the mean velocities in each stream were of the order of .5 m/s, it was noticed that the interface between the two streams was not a straight line, but rather a wavy pattern (Fig. 2a). The wavelength was comparable in size to the duct width, and the pattern appeared to be convected with the mean velocity of the two streams. The amplitude appeared to depend on the difference in velocity of the two streams, and when this was large the pattern appeared to be a row of vortices (Fig. 2b).

The pattern could be disturbed by violently tapping on the plexiglass near the splitter plate, but the disturbance would merely convect downstream with amplification, and without causing any flow instability.

Although the wavy pattern (or pattern of vortices) was intermittent and not strictly periodic, it did have a definite frequency which could be associated with it. For the values used earlier (mean velocity .5 m/s; wavelength of order of duct width, or .04 m), this corresponds to a frequency of 15 Hz - 20 Hz, as was observed.

I the preliminary experiments, the velocities of the two s*'eam were adjusted until this wavy pattern was visible,

and then a loudspeaker was placed at the end of the duct and directed upstream. Frequencies from 1 Hz to 20,000 Hz were scanned in an attempt to excite the flow. In one instance a noticeable increase in mixing was observed when the frequency was 687 Hz, though this could not be repeated and no explanation has been found. In several instances, when the frequency of the loudspeaker matched that of the vortices, around 20 Hz, a dramatic effect was produced on the streams : the smoke (previously only in one stream) was nearly uniformly mixed in both streams from the time they left the splitter plate. This was very encouraging but not very repeatable. It was detected several times but not every time excitation was attempted.

Since 20 Hz is below the threshold of hearing, and since the loudspeaker seemed to perform well at all frequencies in the audible range, it was not until later that it was discovered that it does not perform well at 20 Hz, with measured intensities less than 30 dB in a 1% band around 20 Hz. This is so low it raised the question of how it could have any effect at all.

One possibility which would explain this and also explain the problem of repeatability is that a duct resonance was excited. The duct was 4.5 m long, with one end open and one end closed. If the closed end is acoustically "hard", then the lowest resonant frequency would be that for which the duct was one-fourth of a wavelength, or 18 Hz. The explanation for the lack of repeatability would be this : the frequency of the loudspeaker would always be set equal to the characteristic frequency of the wavy pattern, but it was only when both of these matched the resonant frequency of the duct that high enough amplitudes would exist to create excitation. The flow was adjusted until a readily visible wavy pattern was produced, and this was always in the range of 15 Hz - 20 Hz, but it would have to coincide with the duct resonant frequency for excitation.

This explanation is not complete, however. The resonance excited would consist of a standing wave in the flow direction and should affect both streams in a like manner. No coupling mechanism is proposed, even though the frequencies match. Also, the duct contained some porous material at its upstream end to insure uniformity of the flow, and how this would affect the assumption of an acoustically "hard" wall is not known.

2.2 Experiments with the L-6 wind tunnel

Based on these preliminary experiments, it was decided that experiments should be continued using a new facility. Several factors were considered in the selection of this new facility. Visualization, of course, was felt to be crucial. It was also desired that the flow field should be as simple as possible, meaning two dimensional. The simplest profiles were felt to be two flat plate boundary layers mixing together. The flow field should also be easily controllable and not sensitive to external disturbances. The acoustic source should be able to provide sufficient amplitudes for excitation and should have the ability to operate over a wide range of frequencies.

To fulfill these requirements, the L-6 wind tunnel was chosen, with air as a working medium (Fig. 3). The overall length of this wind tunnel is 5.9 m. The air is injected into each stream using a small blower. The blowers may be independently controlled since each has its own power supply. These drifted in time so that it was difficult to accurately maintain an established velocity, but overall they proved adequate.

After injection, each stream passed through a long duct before reaching a settling chamber. Smoke could be added to one of these streams in this duct. After the settling chamber the air in each stream was accelerated through a contraction ratio of six so that at the exit the flows would be laminar and uniform. The exit dimensions were 20 cm high by 30 cm wide,

divided in half horizontally by a very thin splitter plate.

It was noticed that upon leaving the exit and entering the still atmosphere the two streams were extremely sensitive to external disturbances, such as those caused by doors opening and closing, etc. In addition, when smoke was added to one stream for visualization, large mixing regions near the side of the exit of the streams and the still air made visualization of the region near the splitter plate difficult. To remedy these problems, a plexiglass extension 40 cm long and with the same cross section as the wind tunnel exit was attached to the exit. This provided a region where the mixing near the splitter plate would not be disturbed by external effects and could easily be observed. The extension was kept to a relatively short length because in a longer extension the streams would start to develop parabolic velocity profiles. In addition, in a long duct only a plane acoustic wave could propagate (at the frequencies being used) and the position of the acoustic source would be lost as a free parameter.

When smoke was added to one of the streams, the interface between the two streams became visible. In most instances, it was not a straight line, but a wavy pattern if the two velocities were nearly the same and a row of vortices if they were different (Fig. 4). Presumably, these were variations of the same pattern, marked by different amplitudes. When the vortices were present, they appeared to be contained in a region defined by an angle δ, whose magnitude depends on the velocities of the two streams. The larger the mean velocity of the two streams, or the smaller the difference between the two velocities, the smaller the angle δ. This result, and the general appearance of the vortices, matches that described in the literature (Refs. 2, 4, 5). Neither the wavy pattern nor the vortices were strictly periodic, but rather intermittent. A definite wavelength and period could be attached to this pattern, however, by use of a stroboscope. The frequency appeared to increase with velocity. This, plus the fact that higher velocities meant smaller angles, meant that smaller velocities were better

for purposes of visualization. The main objective in choosing the velocities was the realization of a clear pattern for which a frequency could be determined and which would be as visible as possible. Usually, the velocities were chosen to be in the range of .3 m/s to .5 m/s, and differed by 15% to 20%. Under these conditions, the characteristic frequency and wavelength of the pattern, as determined using a stroboscope near the splitter plate, were 15 Hz to 20 Hz and 2 cm to 3 cm, respectively. At .5 m/s, the momentum thickness near the end of the splitter plate was around .3 cm, so a characteristics distance for the wake would be twice this, or .6 cm; of the same order of magnitude as the vortices.

Again, it should be emphasized that the primary goal was to obtain a qualitative understanding of the process. The first thing which was desired using the new equipment was to see if any excitation at all could be achieved. Accurate measurements of velocity profiles were not felt to be important at that time, rather the concern was for choosing velocities which would make visualization as easy as possible.

The other consideration for assembling a new facility, once the wind tunnel had been selected, was the acoustic source. At first a loudspeaker was used, but when no excitation was achieved it was tested and found to function very poorly in the frequency range considered, as mentioned before. A new device was needed, which would be movable, easily controllable, and which would be able to function efficiently in the frequency range under consideration. In addition, the source should not interfere with the flow, such as a vibrating ribbon might. With these concerns in mind, a device operating on the principle of a siren was constructed. It consisted of an air jet placed near a rotating plate with two holes in it (Fig. 5). The air jet was connected to a 7 kg/cm^2 air supply with a regulating valve to control the pressure. The rotating plate was driven by a small motor connected to a power supply so that the frequency of revolution could be controlled. When one of the holes in the plate passed in front of the jet, a pulse of air

would pass through the hole, thus the frequency of the sound would be twice that of the rotational speed of the plate.

This device worked quite well, although the power supply (thus the frequency) drifted somewhat with time. As might be expected, the acoustic signal was far from a pure tone. Measurements using a Bruel and Kjaer .5 inch condensor microphone and a Bruel and Kjaer frequency analyser showed that the acoustic signal contained roughly 60 dB of each harmonic up to at least the tenth (at a distance of two meters under operating conditions). The directivity was such that the intensity was constant; there was no preferred angle and the siren acted like a point source. This was important, as the siren could be aimed away from the two streams so as not to disturb them because of the air pulsing through the holes, but yet give the same acoustic signal.

When the experiments were performed, the flows would be adjusted until a clear pattern was created, then the frequency of the siren would be set to the frequency of the pattern and varied to cover nearly frequencies. The position of the siren was also varied. No influence of the sound could be detected. The pattern did not become more reguler, nor did the mixing rate seem to change. The frequency was scanned from around 10 Hz to over 30 Hz, which (due to the presence of harmonics) should have effectively covered all frequencies up to 300 Hz.

This was indeed disappointing, and it was not clear what steps should be taken. The literature of classical instability theory was reviewed and as a result several articles were found relating to the problem at hand.

3. LINEAR INSTABILITY THEORY

Before discussing other experiments performed on acoustic excitation, it will be useful to have a brief introduction to linear stability (or instability) theory. This theory deals with small perturbations of a given frequency imposed upon a known mean flow, and decides whether these perturbations are amplified or not. If the perturbations are damped for all frequencies, the flow is stable. If the perturbation is amplified for any frequency, then the flow must be treated as unstable, and will either reach another stable state or will undergo transition to turbulence. This is because any flow will be perturbed to some degree, whether by free stream turbulence, external noise, etc., and this perturbation will in general contain some amount of all frequency components.

The theory as it applies to the current project is only strictly applicable for two dimensional parallel flows. The only flows of this type which satisfy the Navier-Stokes equations are Couette and Poiseuille flows, which have linear and parabolic velocity profiles, respectively. There are, however, cases where changes in the flow direction are much smaller than changes in the direction normal to the flow and for which the flow is near two dimensional. These cases occur when the boundary layer approximations are valid : jets, wakes, mixing layers, and boundary layers, at sufficiently large Reynolds numbers. These may also be treated with sufficient accuracy by the two dimensional parallel flow theory.

A detailed mathematical treatment will not be given here (see Refs. 1, 12), but some basic results important for the project will be stated. The important parameters which determine the stability or instability of a given flow are the velocity profile and the Reynolds number, Re. If the effects of viscosity are negligible (as might be expected in the case of large Reynolds numbers), it may be shown that if the flow is unstable, its velocity profile must have an inflection point (Rayleigh's theorem). It has also been shown (By Tollmien)

that in general the presence of an inflection point means that a flow will be unstable.

Instabilities which occur due to the presence of an inflection point are called "inflection point instabilities". According to the theorems stated it might be assumed that at sufficiently high Reynolds numbers a flat plate boundary layer, which has no inflection point, would be stable. Experiments have shown that this is not the case. This implies that viscosity can play a dominant role, even when the Reynolds number is large, and can cause instabilities to exist in flows which would be expected to be stable. Instabilities of this type are known as "viscous instabilities". Important in this type of instability is the presence of a solid boundary.

Usually there is a critical Reynolds number above which a given flow is unstable. For flat plate boundary layers with no pressure gradient this critical Reynolds number based on momentum thickness is about 200 (Ref. 1). For cases in the absence of boundaries, this critical Reynolds number (based on a characteristic length) is usually much lower; for jets and wakes it is 4 (Ref. 26), and for free shear layers no critical Reynolds number has been found (Refs. 8, 11, 25), meaning that the flow is unstable for all Reynolds numbers. It should be pointed out that at extremely low Reynolds numbers, these flows cannot be treated as parallel and thus the theory does not apply, but the point is that these flows are inherently unstable according to this linearized theory.

Some attempts have been made at non linear instability theories, but usually these are perturbations on linear theories and their range of applicability is low.

4. EXPERIMENTS BY OTHER RESEARCHERS

4.1 Introduction

Before starting on the experimental aspects of the project, attempts were made to find any articles which would somehow shed some light on the problem. One of the difficulties encountered in this attempt was the large number of different topics which are relevant to the problem : acoustics, transition, instability theory, mixing layers, shear layers, large scale structures, etc. All of these are extremely broad topics and to locate all the articles listed under these topics would be impractical. A computer literature search was conducted to locate all articles containing both of the keywords "acoustics" and "shear layers". Approximately twenty articles were found, but none of them proved useful at the time. Some of the articles were in Russian, and many pertained to jet noise. A literature search was also conducted using the card catalogue at the VKI library. A few articles were found on the use of vibrating splitter plates to improve mixing, but these did not prove helpful.

Later, after the experimental results showed no visible excitation, literature pertaining to linear instability theory was searched in an attempt to gain more insight into the problem. As a result, a number of articles were found in which acoustic excitation was used. Why these articles were not found by the earlier searches is not clear.

4.2 Boundary layers

One of the first experiments in which use was made of acoustic excitation is the classic experiment by Schubauer and Skramstad (Ref. 23), one of the first experiments to confirm the results of linear stability theory. Boundary layer oscillations and transition on a flat plate were studied, as were the effects of acoustic excitation on the flow. It was found that acoustic excitation could greatly accelerate transition.

According to linear instability theory, the flat plate (laminar) boundary layer is unstable above a certain Reynolds number, and certain frequencies will be amplified. Free stream turbulence, or external noise, will in general excite some of these unstable disturbances, which will grow until they cause the boundary layer to undergo transition. Thus, the boundary layer can undergo natural transition, but since this is due to random disturbances it will not be repeatable. The introduction of a sufficiently large excitation in the unstable frequency range provides a means for insuring repeatability. Acoustic excitation is one means to do this.

In their experiments, Schubauer and Skramstad used both a loudspeaker and a vibrating ribbon, each in several ways. In one method, the velocity of the flow was fixed and the frequency of the acoustic source was varied. In another, the frequency was fixed and the velocity was varied. In a third method, a feedback loop was used which fed the signal detected by a hot wire in the boundary layer as an input to the acoustic source. The frequencies used varied from 20 Hz to 180 Hz (mostly in the higher part of this range) and the velocities were ordinarily 8 m/s to 35 m/s.

The results of these experiments showed good agreement with linear instability theory. Sound was found useful in providing some control over the transition. The transition itself was found to be gradual for the most part, but sometimes marked by bursting processes.

4.3. Free shear layers

Sato and coworkers have performed extensive studies on a variety of flow fields, including two dimensional jets at high and low Reynolds numbers, axisymmetric wakes, and two dimensional wakes (Refs. 16-22). They studied mean velocity profiles, fluctuating velocity components, and the effects of acoustic excitation on transition. Their findings for the various cases are quite similar to each other, and only results with two dimensional wakes will be discussed in any detail.

From their investigation of a two dimensional wake from a flat plate, they found it possible to divide the wake into a number of regions. The first of these is the laminar region, where no fluctuations are detected and the flow develops from two boundary layer profiles to a profile closely resembling a Gaussian. In the linear region which follows, sinusoidal fluctuations exist which grow exponentially. The existence and characteristics of these fluctuations agree well with linear instability theory. The next region, the nonlinear region, is characterized by higher harmonics of the sinusoidal fluctuation found in the linear region. In the three dimensional region, which follows, the waveform becomes increasingly irregular and three dimensional effects start to occur. Finally, the flow gradually becomes turbulent without any bursts like those found in boundary layer transitions.

In one of the earlier papers, a vortex model was proposed which explained many of the features of the fluctuations and of the mean flow. The model postulates a row of vortices of alternating sign existing in the linear region. This would give rise to a sinusoidally fluctuating velocity. In the nonlinear region, this row of vortices would form a double row, similar to a Karman vortex street. This would explain the presence of the second harmonic. In the three dimensional region, deformation of these vortices would occur until the flow became turbulent. This vortex model also explained some of the puzzling aspects of the mean flow behavior in the various regions. The authors presented few arguments against such a model, except that it failed to explain all parts of the problem, but they appear to have abandoned the model entirely in later papers.

In their experiments a free stream velocity "U" of 10 m/s was used. This gave a Reynolds number (based on the width of the wake "d") of around 3000. The frequency "f" of the natural fluctuations was around 700 Hz, corresponding to a Strouhal number (St = fd/U) of 0.6. Sound from a loudspeaker

at frequencies between 480 Hz and 850 Hz was found to excite oscillations in the linear region of the same frequency, while sound at other frequencies had no effect. Presumably, this was the range of unstable frequencies; other frequencies would cause disturbances which were stable, and thus would not have a visible effect. The effect of acoustic excitation increased with the intensity of sound up to a certain level, above which the effect remained the same.

In later experiments, sound containing more than one frequency component was used as excitation. Interesting results were found. When the sound contained two frequencies in the unstable range, both of these components behaved independently in the linear region. In the nonlinear region the two components interacted with each other as well as with the mean flow. Harmnics, and frequency components at sums and differences of the two frequencies and their harmonics, were found. It was found that if one of the two components had a larger amplitude than the other, it would grow at the expense of that other component. The same was true for the natural oscillation. This "suppression" effect was found to be greater the closer the two frequencies were.

Another effect was discovered, or at least reported for the first time, after more than fifteen years of experimentation by Sato using what appeared to be the same experimental facilities. This is that sound delays the transition of the wake. Later experiments showed that it can accelerate transition as well, depending on the frequency. Sound of a frequency near the natural frequency caused a delay in transition, with more delay the closer the frequencies were. Sound of a frequency farther away from the natural frequency was found to accelerate trandition, while sound at frequencies very far away had no effect.

The explanation given by the authors is not very satisfactory. They explain that if the excitation and natural frequencies are very different, nonlinear interactions will be

will be greater and transition will be accelerated. If the two frequencies are close there should be a suppression of the natural frequency which would result in a delay of transition.

This is quite inadequate. Even if the natural oscillation is suppressed, the other frequency could be expected to go through the nonlinear and three dimensional regions tc transition as the natural oscillation would. When the excitation frequency coincides with the natural frequency, the transition would be expected to proceed as normal, even perhaps a bit sooner. Since the initial amplitude would be greater the nonlinear region might occur sooner, but there should certainly not be a delay in transition. Presumably, more work will follow.

From these experiments; some basic aspects of the acoustic excitation of flow instabilities can be understood. Left to itself, a wake (or other unstable flow) will undergo transition due to instabilities excited by background turbulence or other random effects. The frequency of the natural oscillation will be the frequency which is most unstable in some sense. This oscillation will grow exponentially in the linear region until nonlinear, and eventually three dimensional, effects will predominate and turbulence will gradually follow. When an acoustic excitation is present, the only effect is to cause an initial disturbance of sufficient amplitude. It grows as expected in the linear region, but in the nonlinear region its growth affects and is affected by other components, such as the natural oscillation. Thus the effect of sound is only to trigger the initial disturbances, not to continually pump energy into the growing disturbance. The reason for using acoustic excitation is to provide some control over transition, which would otherwise be caused by random effects.

Some other experiments have been performed on the effects of acoustic excitation on shear layers, a few of which will be discussed here. Browand (Ref. 3) investigated the effect of acoustic excitation on a free shear layer caused by the separation of a laminar boundary layer from a rearward-

facing step, giving a velocity profile as shown in figure 6. He compared the natural transition and the transition when acoustic excitation was used at a frequency 10% greater than the natural frequency (79 Hz at a free stream velocity of 5 m/s). It was found that the results were qualitatively the same with and without excitation, except that repeatability was greater with excitation. In each case, both higher harmonics and subharmonics were found. The wave speed of the natural oscillation was found to be about .6 of the mean velocity. In some cases, effects similar to "bursts" were seen, although the author was hesitant to call them bursts, since they were much smaller in amplitude than bursts seen in boundary layers. This investigation appeared to be the only one involving a free shear layer of any type (jets, wakes, mixing layers) for which these "bursts" if indeed that is what they were, were found.

In another set of experiments, Miksad (Refs. 14, 15) studied the transition of acoustically excited shear layers with emphasis on the nonlinear region. He classified the instability into several regions, but the basic scheme is similar to that proposed by Sato. His experimental facilities consisted of a wind tunnel with a splitter plate and two flows of very different velocities. One of his flows was at 2 m/s, the other at .3 m/s. The frequency of natural oscillations was 16 Hz. A loudspeaker was mounted in the settling chamber of the wind tunnel and used at a frequency of 29 Hz. The author stated that he felt the principal effect of the excitation was to shift the position of the stagnation point on the splitter plate, thus injecting vorticity into the shear layer. To support this, he states that a loudspeaker placed downstream was ineffective in exciting disturbances.

This is very different from the mechanism of instability described by Sato. In Sato's case, the loudspeaker was not mounted upstream in the settling chamber and the effect of the acoustic excitation was to provide an initial disturbance which would then undergo the natural process of growth

to transition. The effect of the excitation in this present case is to change the nature of the flow near the edge of the splitter plate - quite different.

The results obtained by Miksad in his first paper were mainly concerned with detailed behavior in the nonlinear and three dimensional regions. In his second paper (Ref. 15), a study was made when two frequencies (22 Hz and 28 Hz) were used simultaneously for excitation. The results were very similar to those reached by Sato, with a number of harmonics, subharmonics, and sum and difference tones present. The main emphasis again was on the detailed behavior of the nonlinear region, and no new conclusions were reached which were helpful to the present project.

4.4 Axisymmetric jets

Several sets of experiments have also been performed involving acoustic excitation on the behavior of axisymmetric jets (Refs. 7, 9, 10, 27). A primary motivation for these studies appears to be an understanding of jet noise, particularly in reference to commercial aircraft. One study of this case is that of Crow and Champagne (Ref. 7), who investigated orderly structure in turbulent jets over a wide range of Reynolds numbers. Acoustic excitation at frequencies from 100 Hz to 300 Hz was made possible using a loudspeaker mounted upstream in the settling chamber of the wind tunnel. When forcing was performed at the natural frequency (the velocity was always adjusted so that this corresponded to a resonant frequency of the wind tunnel), the results showed fairly good agreement with linear instability theory. Excitation at frequencies other than the natural frequency produced similar results, but the effects were not as great. It was also found that excitation at the natural frequency could significantly reduce background turbulence.

Other experiments on axisymmetric jets have been performed by Zaman and Hussain (Refs. 10, 27), whose primary interest was in the mechanics of vortex pairing. They studied

acoustically excited jets over a wide range of Reynolds numbers and Strouhal numbers, and in cases where the initial boundary layer was laminar and turbulent. Two modes of vortex pairing were found which are independent of each other over a wide range of conditions : the shear layer mode, and the jet column mode. The shear layer mode consists of the pairing of thin vortex rings near the exit of the jet when the initial boundary layer is laminar. The jet column mode, which corresponds to the mode seen by Crow and Champagne, consists of pairing of thick vortex rings at two diameters downstream. These vortices were convected downstream with a velocity .6 of the mean velocity of the jet.

Acoustic excitation from 70 Hz to 3500 Hz was made possible by a loudspeaker mounted in the settling chamber upstream of the exit. The frequency was set to coincide with a resonant frequency of the wind tunnel. The excitation proved helpful in establishing repeatability of the vortices.

In these experiments by Crow and Champagne and by Zaman and Hussain, the effect of acoustic excitation appears to have been to create a surging at the exit, and thus produce vorticity, as in the experiments of Miksad. Although Zaman and Hussain contend that the acoustic excitation did not create any artificial structures but only triggered naturally occurring ones, the effect is of a more global nature than in the case of Sato, where the acoustic excitation only produced an initial unstable disturbance.

4.5 Mathematical studies

There have been a few papers of a mathematical nature which may relate to the topic of acoustic excitation of instabilities. A classic paper by Chu and Kovasznay (Ref. 6) deals with nonlinear interaction in a gas and predicts some coupling between shear layers and sound, though not in any way which would yield insight into the problem. Their paper basically

establishes a scheme whereby (in theory) all interactions can be classified and computed. An ordering principle based on a characteristic amplitude is developed. When this amplitude is not small, or when it is growing exponentially, as in the case of an instability, this scheme is not useful.

Recently Tam (Ref. 24) published a paper on the excitation of instability waves in a two dimensional shear layer by acoustic disturbances. He formulated the problem mathematically and found a general solution showing the dependence on various parameters such as Machnumber, frequency, etc. Unfortunately, the author has appeared to miss the physics of the problem entirely and his conclusions show no correspondence with established experimental results. For instance, he states that excitation depends strongly on wavelength matching of the instability wave and the acoustic wave, not frequency matching (as all the experiments have shown). He also makes other statements at variance with established experimental results. In short, the paper is of no help at all in the understanding of the process.

5. CONCLUSIONS

From the discussions on instability theory and on other work done on the topic of acoustic excitation, as well as on the experiments performed, several conclusions may be reached. The first, and primary conclusion, is that under certain circumstances sound can play an important role in enhancing the mixing of parallel streams. This conclusion is based not only on the preliminary experiments performed in this project, but also on other reports which have shown that sound may play an important role in exciting instabilities.

Whether or not sound may play a role depends on several factors. One of these is the type of flow field. From the results of the experiments done, as well as from instability theory, it may be concluded that the type of the instability, whether it is an inflection point instability or a viscous instability, is important in determining the magnitude of the effect of acoustic excitation. Transition in boundary layers, which are unstable due to an instability of the viscous type, is marked by sharp, irregular bursts. This is very different from free shear layers, which undergo gradual transition.

The various flow profiles which have been considered experimentally are shown in figures 7 and 8. The first two show velocity profiles in the duct used last year at various axial locations. Before the splitter plate both streams are parabolic. Afterwards, each profile contains two inflection points. The next two figures show velocity profiles for the L-6 wind tunnel, again at various axial locations. Before the splitter plate these are Blasius profiles. Each of the profiles downstream of the splitter plate also containd two inflection points.

All of the profiles contain inflection points, so in the limit of negligible viscocity each should be unstable. There is a crucial difference between the first two profiles and the second two profiles, however, and that is that the

first two have a nearby solid boundary. This means that the first two may also have viscous instabilities, which are marked by bursts. It was believed this was what occurred in the preliminary experiments. A bursting type effect was definitely what was observed in the enhanced mixing under acoustic excitation. The fact that the profile contained inflection points may also have played a role, but this is not known.

After having observed such a dramatic enhancement of the mixing under acoustic excitation, the same effect was expected when using the L-6 wind tunnel. The difference between the two types of instabilities was not understood at the time, and this expectation seemed logical, though it is now seen to be unrealistic.

Transition in free shear layers is a gradual process, so probably no visual observation would have detected the effect of the acoustic excitation. In addition, the results of Sato and others showed that sound may accelerate or delay transition, depending on the frequency content of the sound. The siren which was used for the experiments with the L-6 wind tunnel produced many harmonics as well as much broadband noise so even if it had enough intensity it is unsure if the effect would be positive or not.

Another factor which may be important in the excitation process is the location of the source and the environment of the flow. From a study of other experiments performed involving acoustic excitation, there appear to be two very different mechanisms by which sound can excite instabilities in a flow. The first one is that used by Sato, among others, in which the effect of the sound is only to trigger an initial unstable disturbance which will be amplified by the flow. In this respect it is no different than the effect of free stream turbulence or any other cause of natural instabilities, except that it is a regular disturbance. This is why acoustic excitation is often used as a means for insuring repeatability. This is a very local effect, for once the initial instability is triggered in this manner the sound plays no further role.

The second mechanism by which sound may excite insta bilities is seen in the experiments of Miksad as well as the experiments on axisymmetric jets. In all these cases a loud-speaker was used inside a duct to create a surging effect at the exit of the jet (or at the splitter plate, whichever the case may be). This is believed to cause the stagnation point near the exit of the jet (or on the splitter plate) to change with time, injecting vorticity into the flow (this explains why Miksad had no effect when he place the loudspeaker outside the flow). This is a global effect and is the same as having a vibrating splitter plate or a jet exit which changed its diameter with time.

After having seen that sound may play an important role in the mixing process, it may be useful to discuss again the experiments performed during this project, especially in comparison with other experiments reported. Several fundamental differences may readily be seen. The first involves the magnitude of the frequencies used. In the present project, due to the requirement of visualization, the velocities were kept below 1 m/s and the frequencies near 20 Hz. Although Miksad used frequencies in this vicinity, most other experiments used frequencies which were much higher, usually several hundred hertz. This made it possible to achieve much higher intensities than were possible in this experiment. The loudspeaker used could not give appreciable intensity at the low frequencies used, and the siren could give moderate intensities, but not at a single tone. Higher frequencies would have meant that substantial intensities could be achieved using the loudspeaker, although it would have meant visualization would have to be abandoned.

All the other experiments used hot wires and required large amounts of data analysis. When visualization was used it was with the help of a high speed camera. This was because in most of the other experiments, it was realized that bursting events are not characteristic of free shear layer transition, and that other means than visualization should be used to determine the effects of excitation. In addition, acoustic

excitation was often used as a means to insure repeatability of the transition while the actual desire was to measure fluctuating velocity components, mean velocity profiles, etc. for which data analysis and the use of hot wires would be necessary.

6. RECOMMENDATIONS

It has been shown that sound can greatly enhance mixing under certain conditions. Exact definition of these conditions is difficult, as they depend strongly on several factors : flow geometry, source location, the presence or absence of solid bodies, the frequency content of the excitation, etc. It is felt that in any further experiments, the actual situation under study should be matched as closely as possible. Any simplifications, such as studying a free shear layer instead of a constrained shear layer or moving the position of the source, can change the type of the instability as well as the mechanism for interaction. The motivation for the study is the mixing process of a chemical laser, which consists of a large number of parallel streams. In the duct used last year, two of these streams were modeled. Whether this changes significant features of the process or not is unclear, but it is recommended that the actual configuration should be modeled as closely as possible.

Of course, Reynolds numbers and Strouhal numbers should be kept the same in any scaling process, as these are felt to be important. Due to the presence of solid boundaries viscous instabilities may be present and Reynolds numbers may be important even if they are large. From a practical viewpoint, it would be preferable to use small dimensions and high frequencies, as these will be easier to produce. Other means of determining the effects of the excitation should be found besides observation. Preferably some quantitative method may be used.

In review, it has been shown that acoustic excitation may play an important role in exciting flow instabilities, and may enhance the mixing of two parallel streams, This excitation depends on a variety of factors, and may occur through two different mechanisms. These conclusions explain the experimental results found and lead to recommendations for further research on the same topic.

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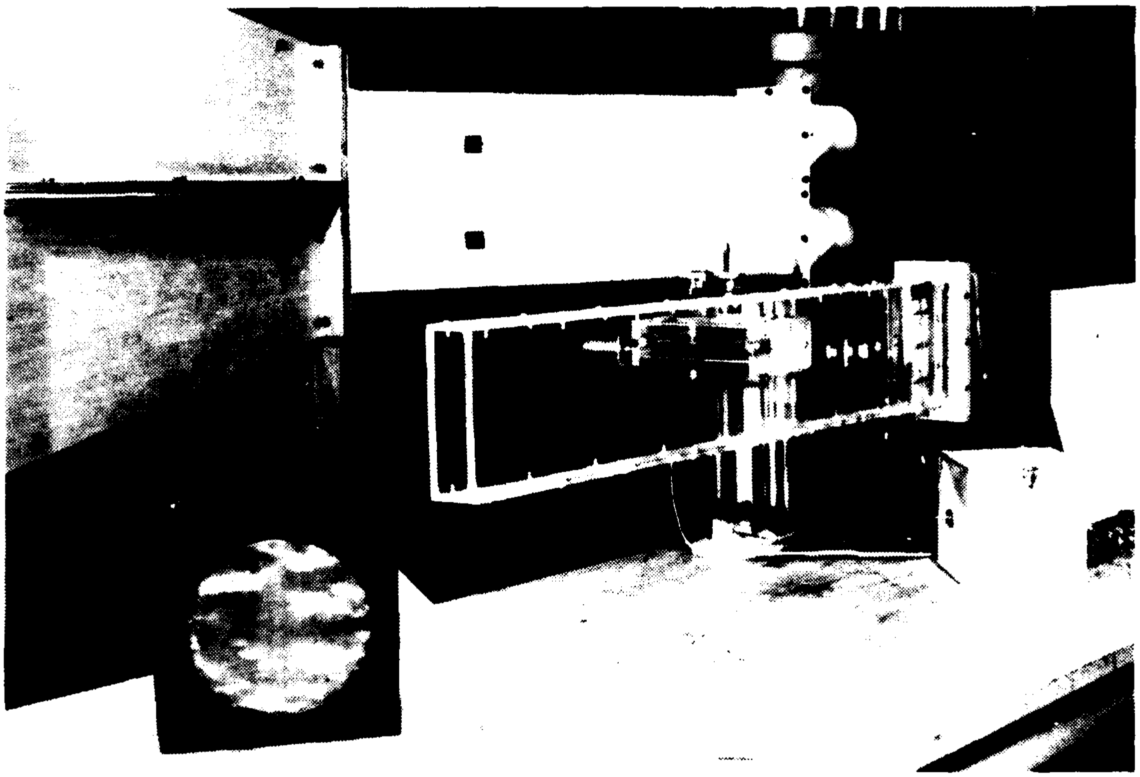

FIG. 1 - DUCT USED IN PRELIMINARY EXPERIMENTS

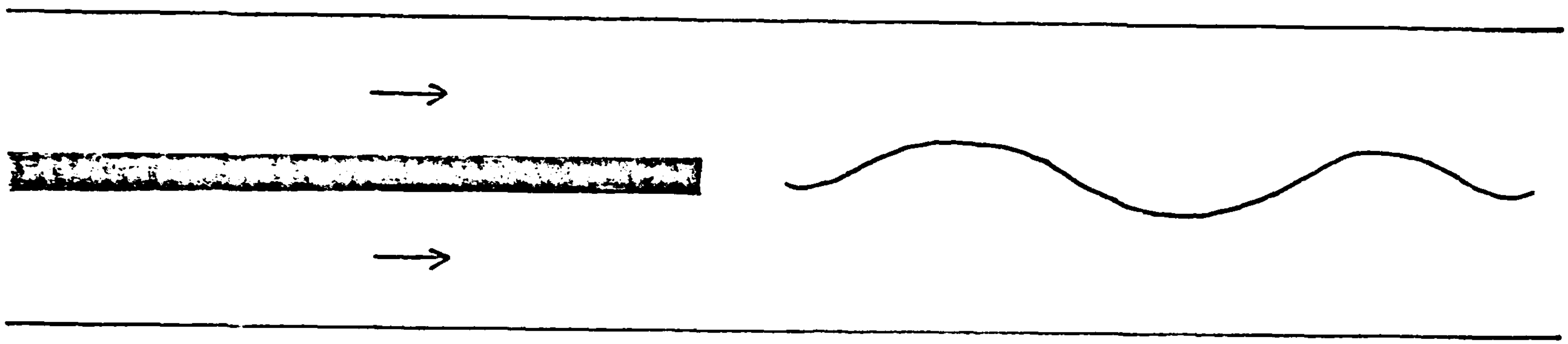

FIG. 2a - WAVY PATTERN IN DUCT

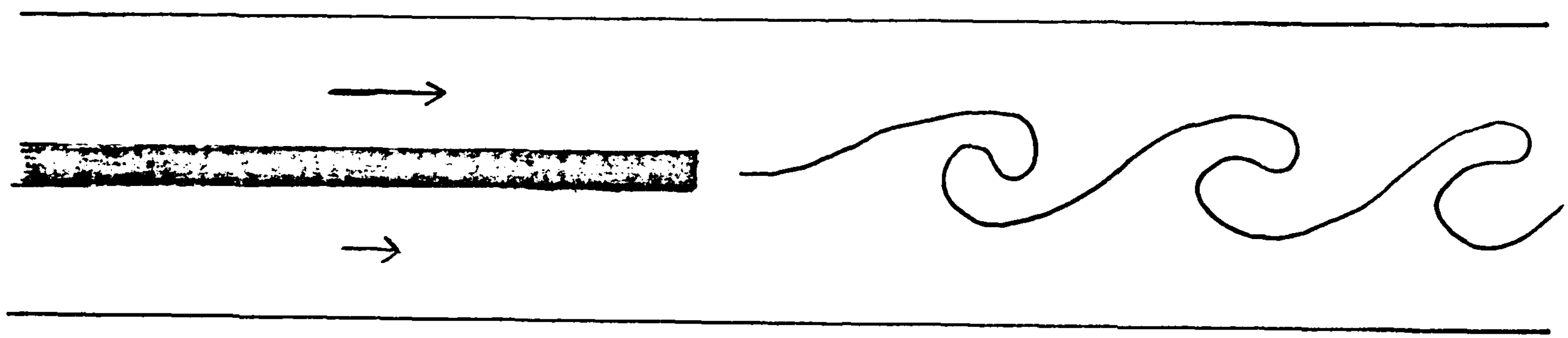

FIG. 2b - PATTERN OF VORTICES IN DUCT

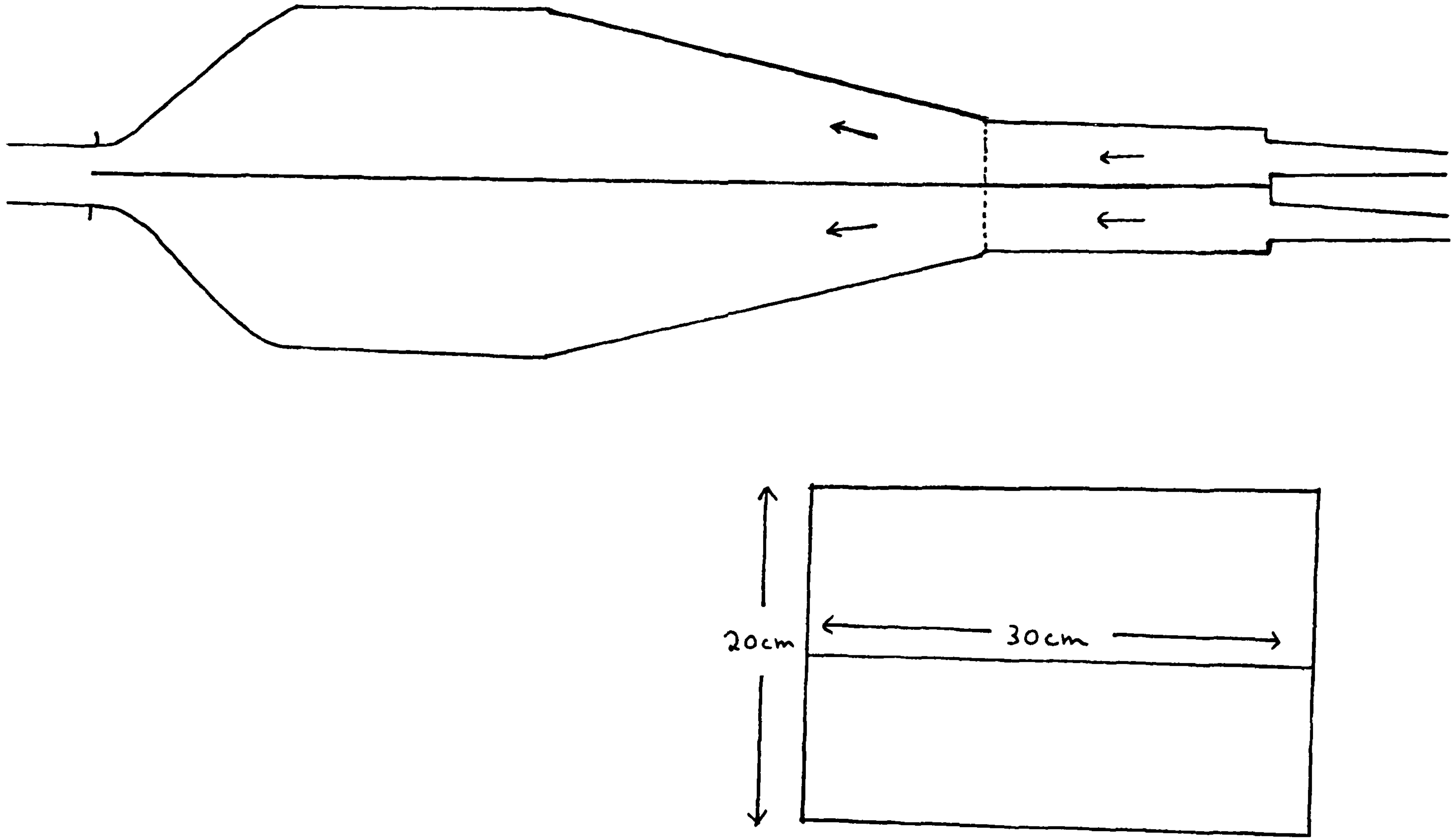

FIG. 3a - L-6 WIND TUNNEL; SIDE VIEW + FRONT VIEW

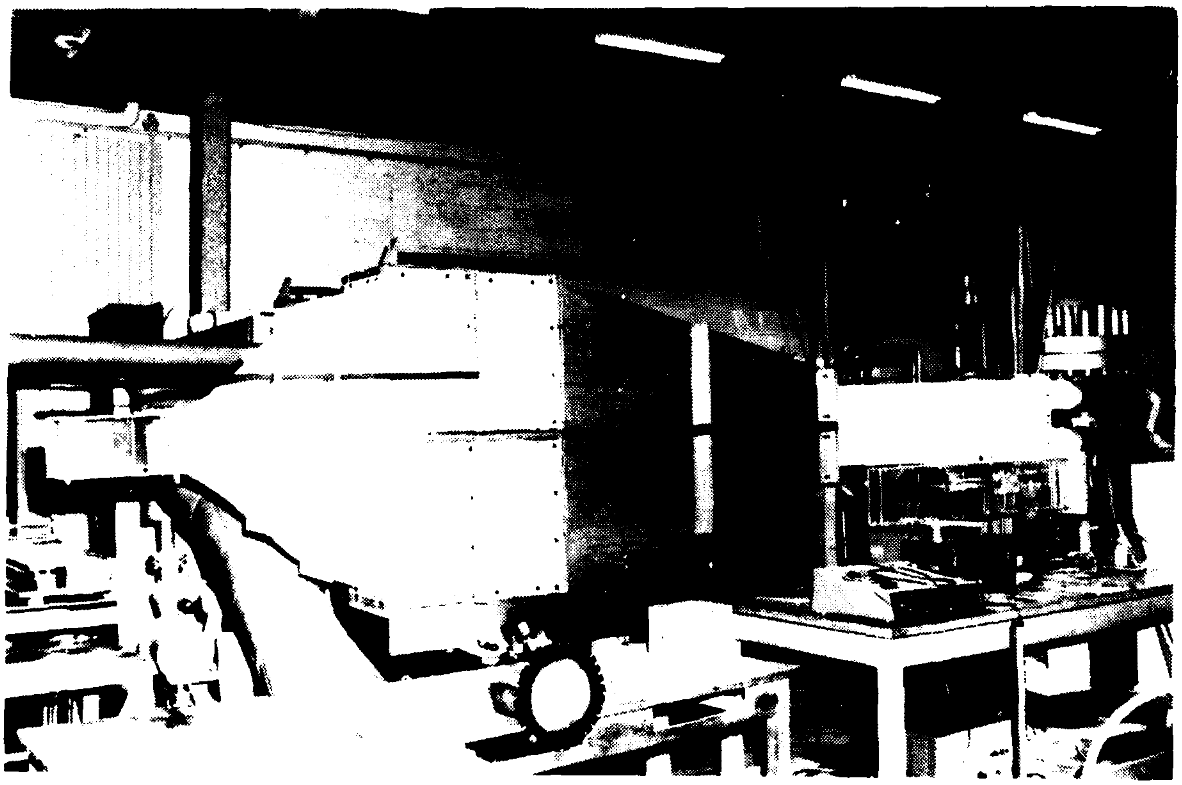

FIG. 3b - L-6 WIND TUNNEL

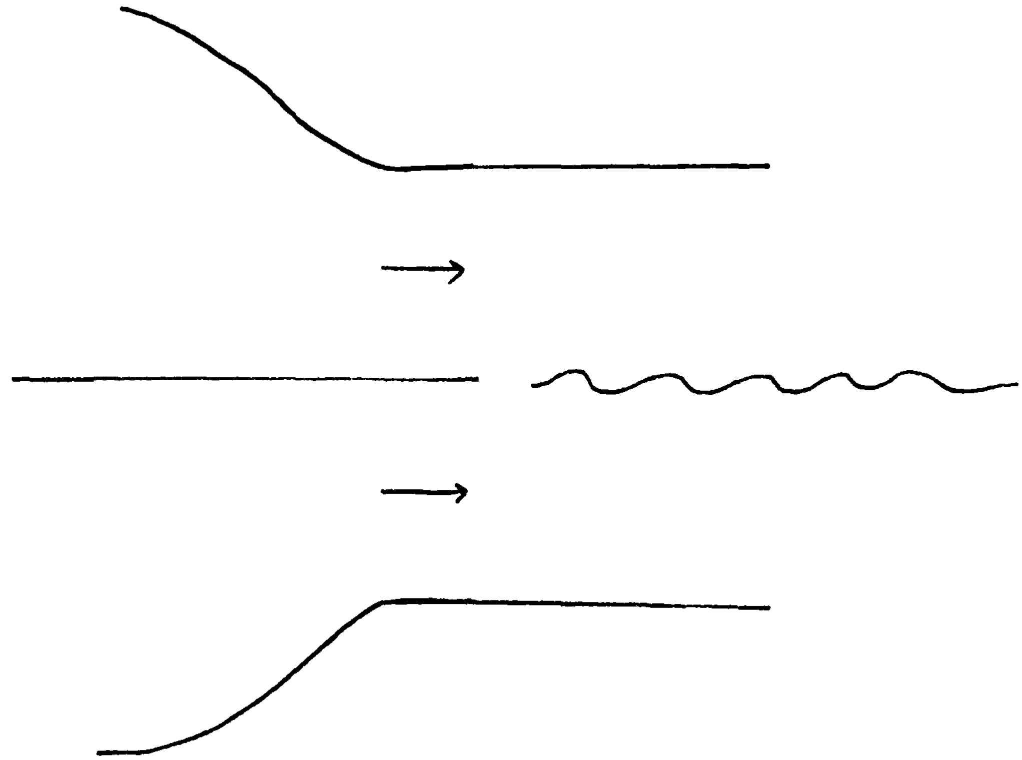

FIG. 4a - WAVE PATTERN FROM L-6

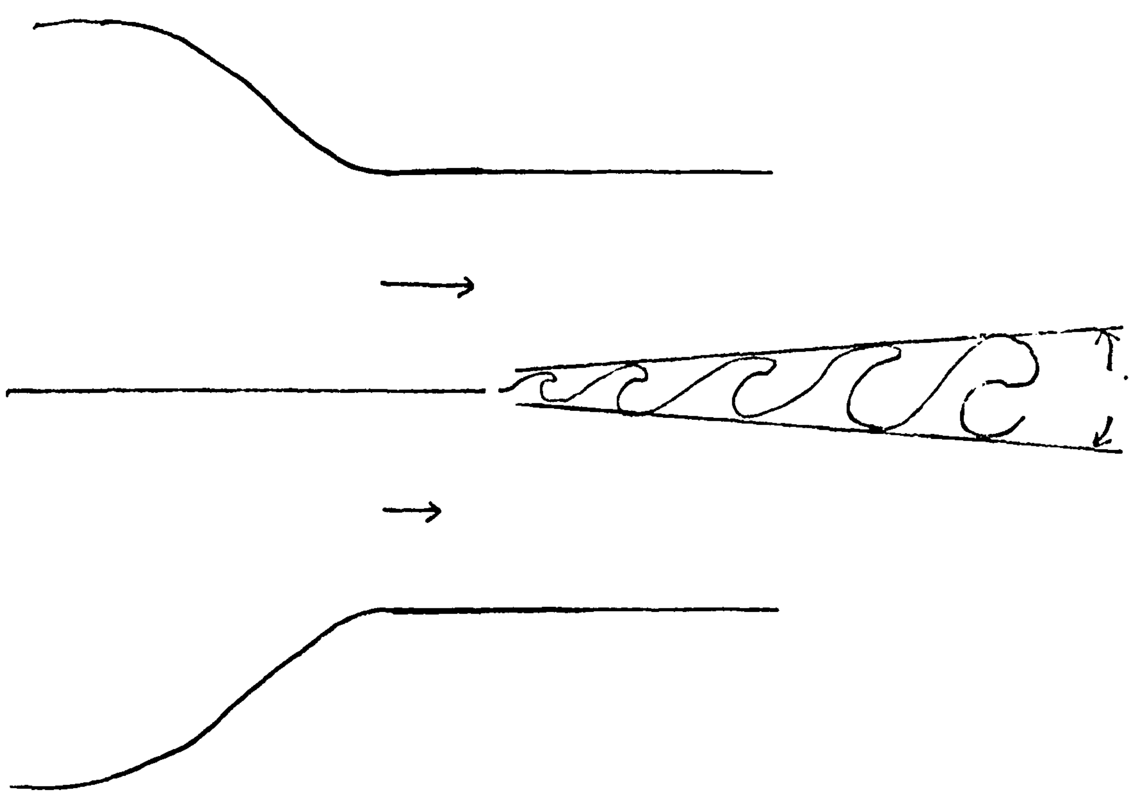

FIG. 4b - PATTERN OF VORTICES FROM L-6

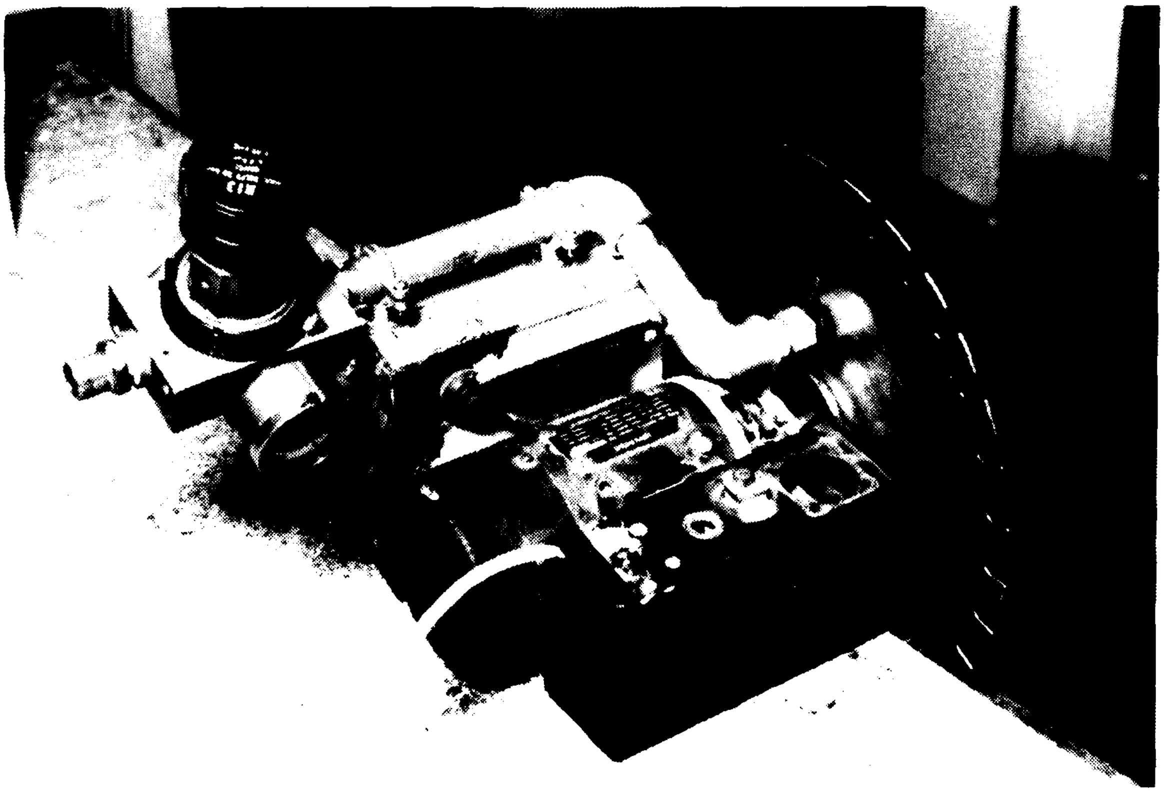

FIG. 5 - SIREN

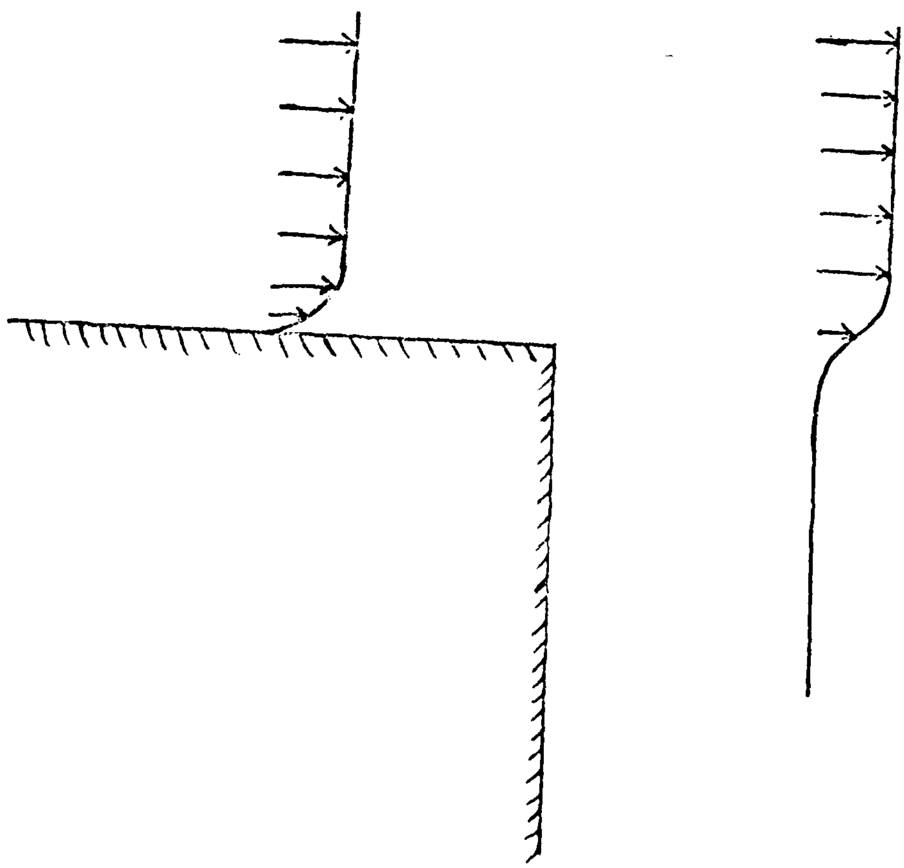

FIG. 6 - EXPERIMENTAL ARRANGEMENT OF BROWAND

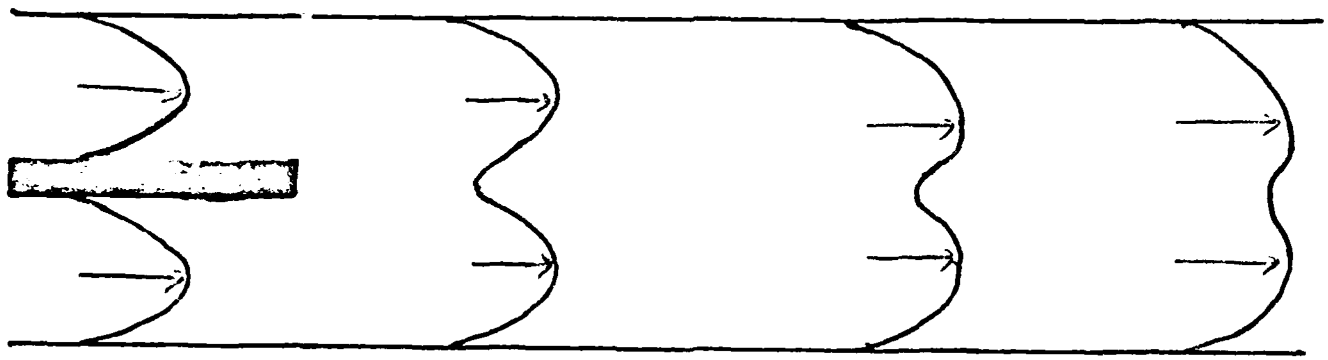

FIG. 7a - VELOCITY PROFILES IN THE DUCT WITH THE SAME MEAN VELOCITY IN EACH SIDE

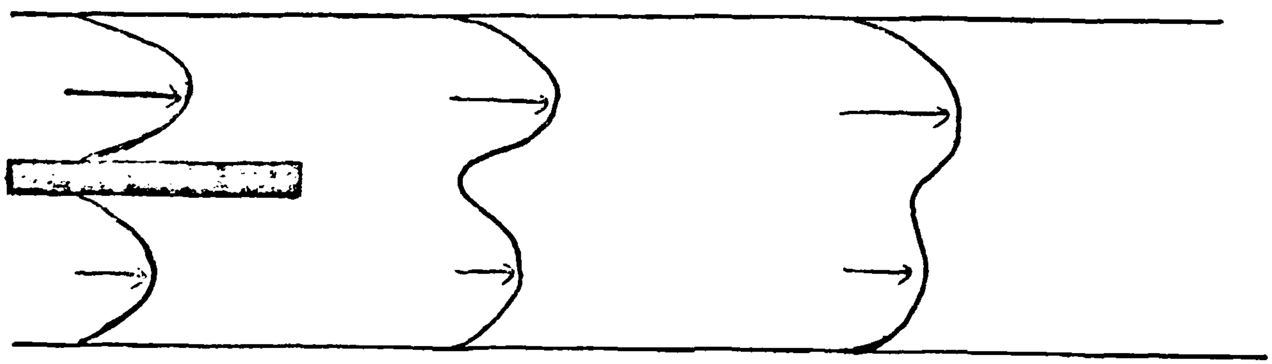

FIG. 7b - VELOCITY PROFILES IN THE DUCT WITH DIFFERENT MEAN VELOCITIES IN THE TWO SIDES

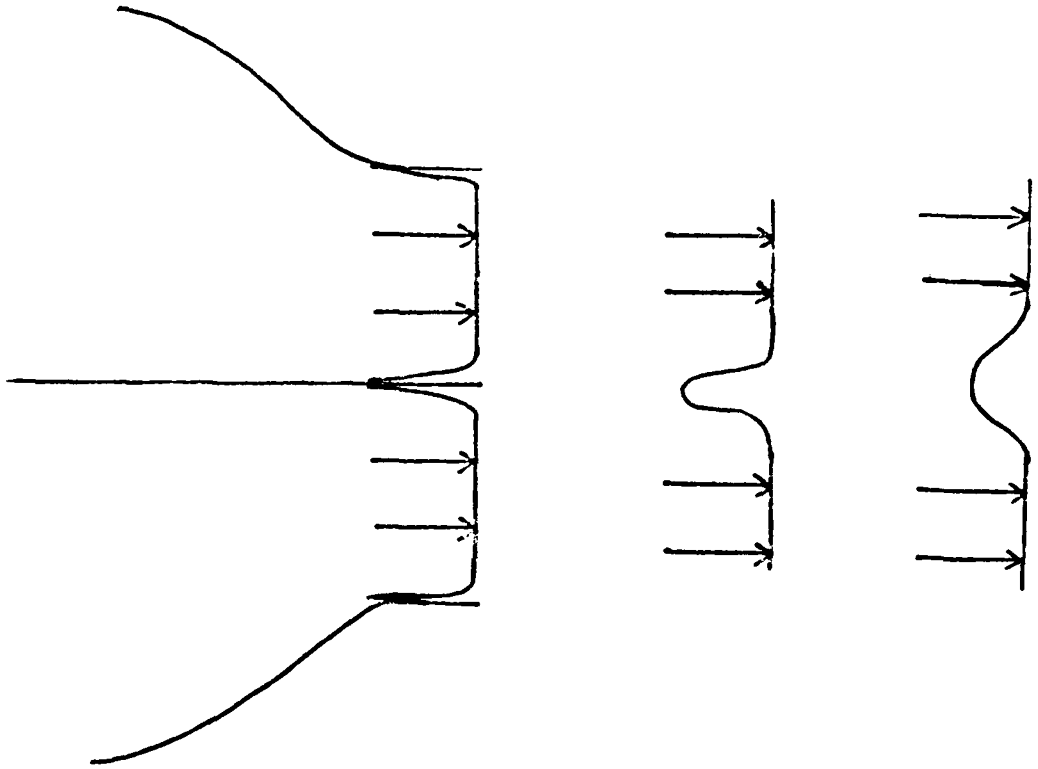

FIG. 8a - VELOCITY PROFILES FOR THE L-6 WITH THE SAME MEAN VELOCITY IN EACH SIDE

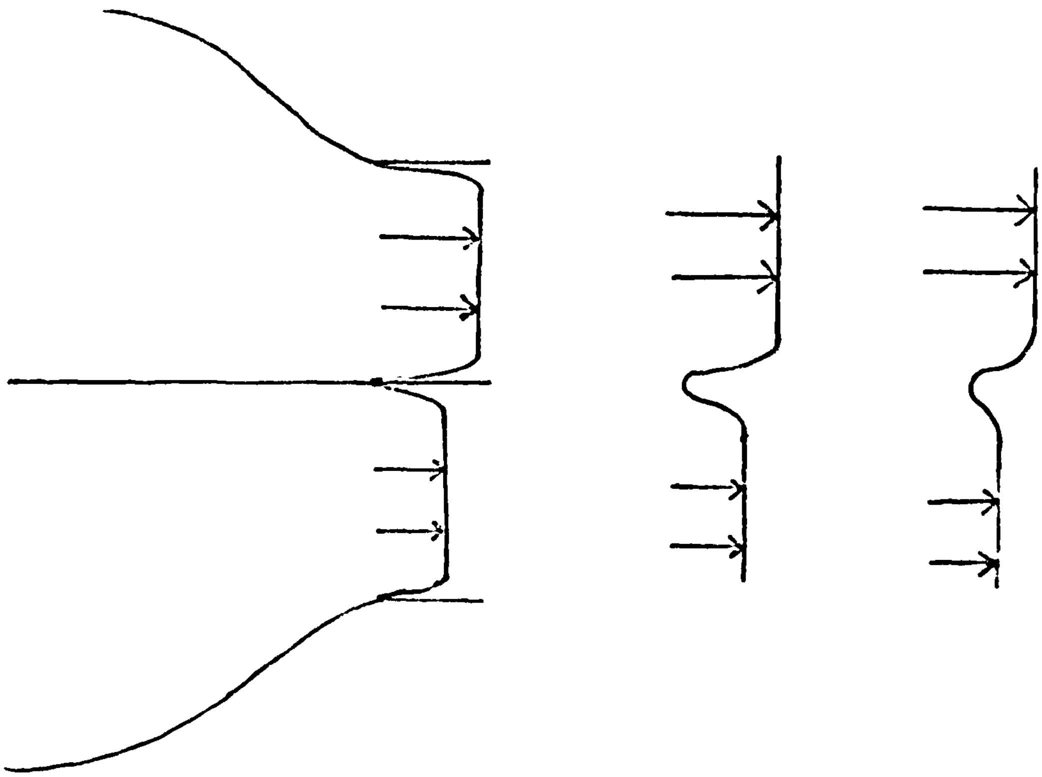

FIG. 8b - VELOCITY PROFILES FOR THE L-6 WITH DIFFERENT MEAN VELOCITIES IN THE TWO SIDES

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